



Experimental Study of Beam Energy Spread in Space-Charge-Dominated Electron Beam*

Y. Zou, Y. Cui, A. Valfells, R.A. Kishek, S. Bernal, I.Haber, H. Li,
M. Walter, B. Quinn, M. Reiser

and P. G. O'Shea

Institute for Research in Electronics and Applied Physics

University of Maryland

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Outline

- Motivation
 - Mechanism of beam energy spread increase in intense beam.
- Experiment design to characterize the energy spread and its evolution in the electron beam
- Design of a compact high-precision energy analyzer
 - Four issues to affect the analyzer resolution
- Phase I experimental results and its comparison with the theory
- Discussions and future work



Energy Spread Growth in the Intense Electron Beam

- Longitudinal-transverse relaxation (intra beam scattering) [1]
 - Long relaxation time
- Longitudinal-longitudinal relaxation [2]
 - Short relaxation time, ~ plasma period
- Theoretical prediction for the longitudinal energy spread including both effects is given by: [3]

$$\Delta E_{\parallel, rms} = [(2qV_0 k_B T_{\parallel})^2 + (C / \rho e_0) q n^{1/3} q V_0]^{1/2}$$

- Scaling law for the energy spread due to the L-T relaxation:

$$\Delta E_{rms} \sim (I * D / a)^{1/2} \sim (J * a * D)^{1/2}$$

[1] See the reviews in Chapters 5 and 6 of M. Reiser, “Theory and Design of Charged Particle Beams”, John Wiley & Sons, 1994.

[2] See, for instance, A. V. Aleksandrov et al. Phys. Rev. A, 46, 6628 (1992) **UMER**

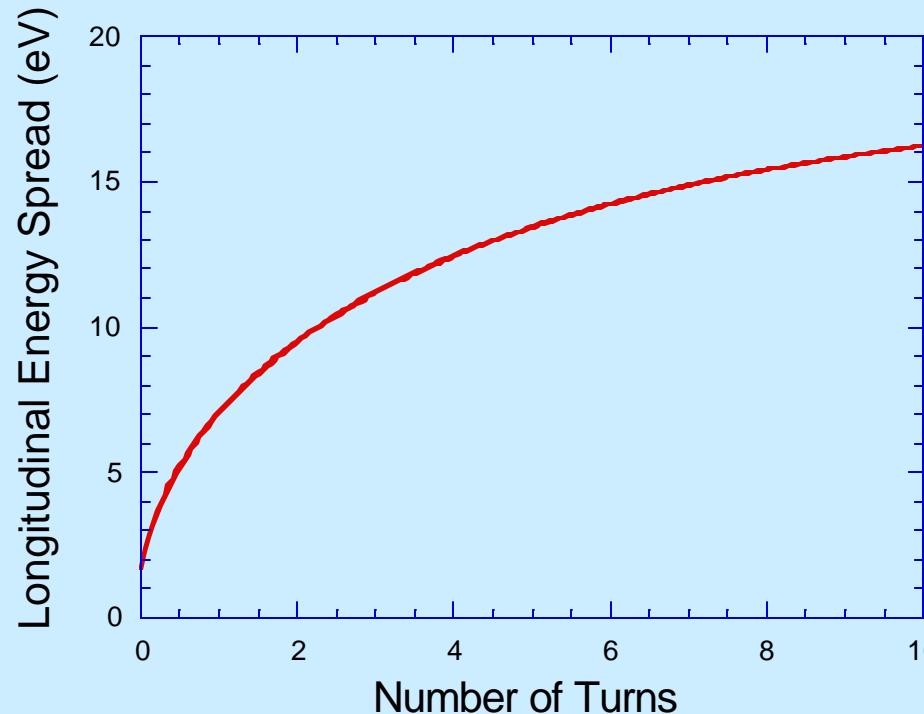
[3] Y. Zou, Electrical and Computer Engineering, Ph.D Dissertation, 2000



Energy Spread Growth in UMER

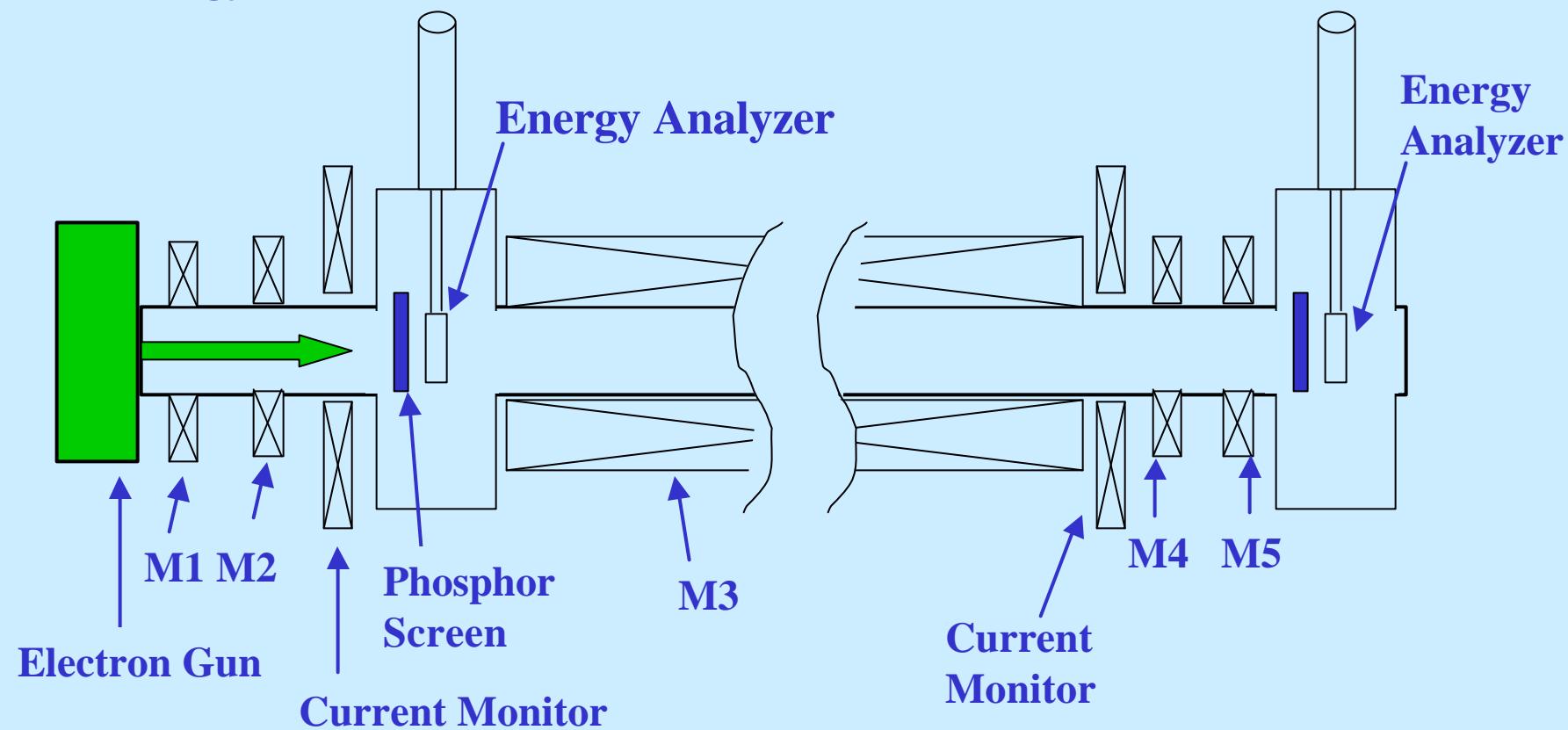
- University of Maryland Electron Ring (UMER) project
- Nominal beam parameters:
 - Energy: 10 keV,
 - Current: 100 mA,
 - Average radius: 0.01 m,

Theoretical Calculation of Energy spread due to L-T and L-L effects



Experiment Design to Study the Energy Spread Evolution in a Linear Channel

- Long Solenoid Channel Experiment (Length: 2 m)
 - Energy analyzer test bed
 - Study the energy spread evolution in linear beam line due to intra beam scattering, mismatch, instability ...
- Beam parameters:
Energy: 1~5 keV, Current: 12 mA ~ 150 mA

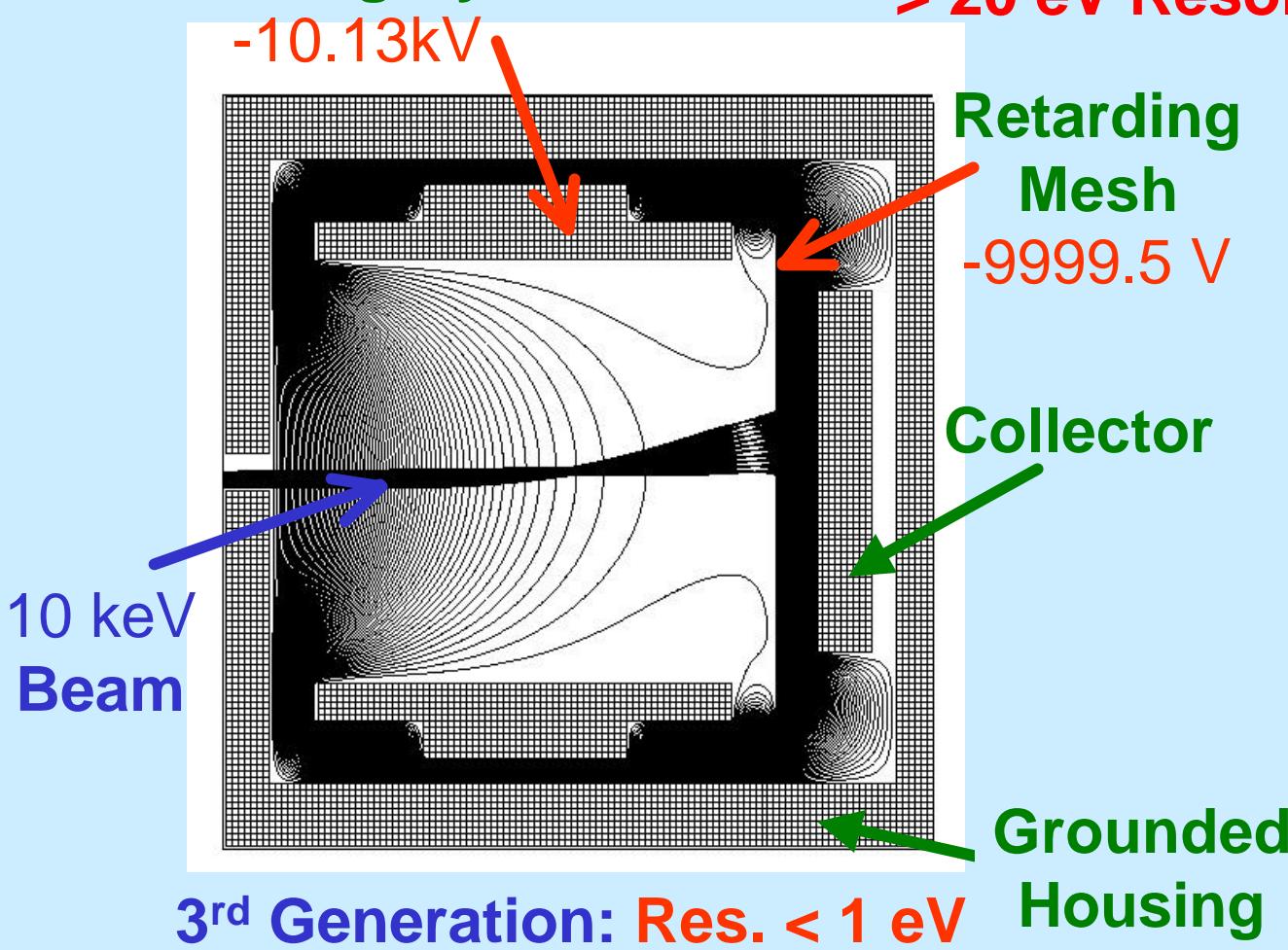




Energy Analyzer Development

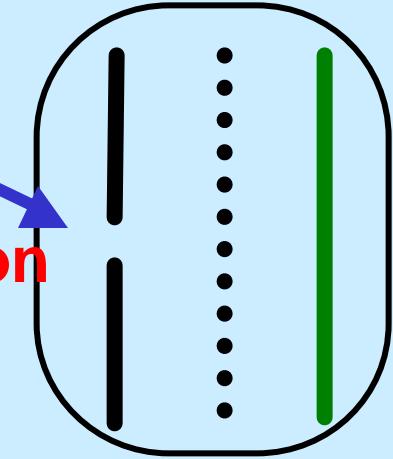
Collimating Cylinder

-10.13kV

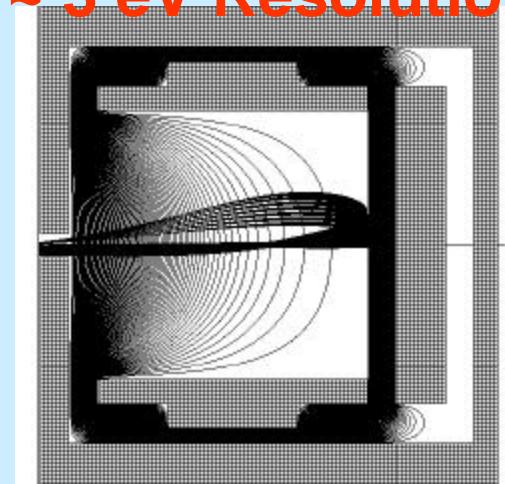


3rd Generation: Res. < 1 eV

1st Generation:
Parallel-Plate
Retarding EA
> 20 eV Resolution



2nd Generation
~ 3 eV Resolution

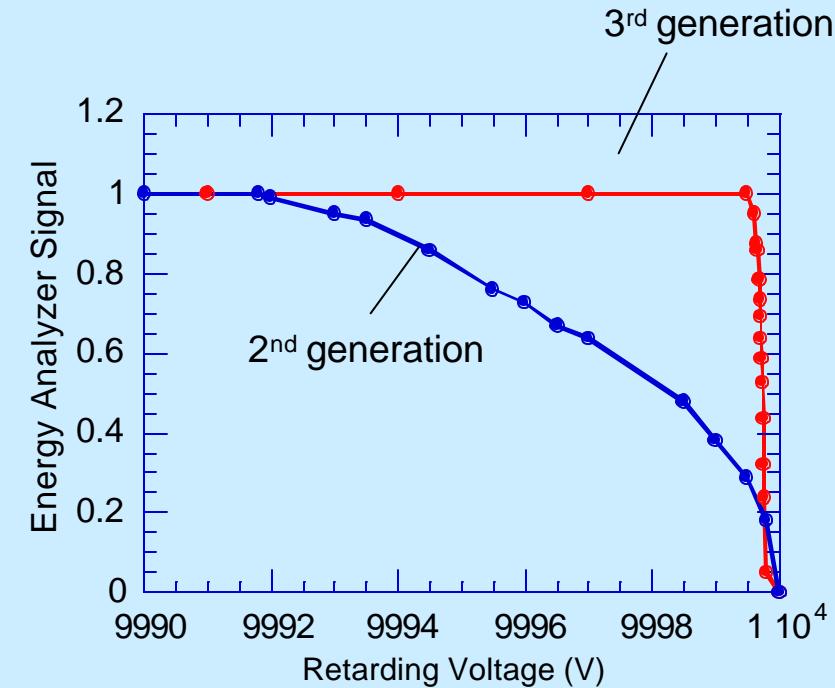
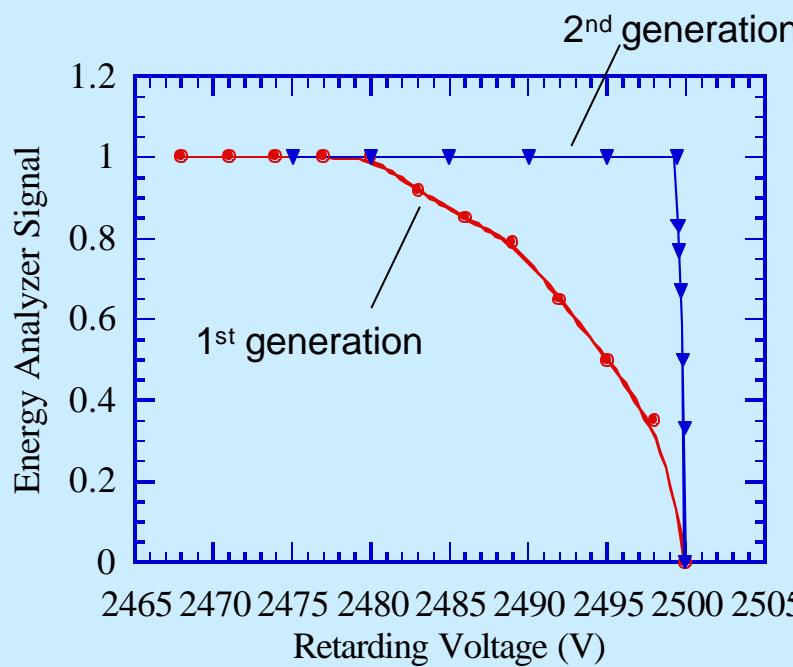


Issues in the Analyzer (1)

Problem: Transverse defocusing due to space charge and beam emittance.

Solution: Use a cylindrical electrode to focus the beam.

Result: Resolution improved by more than one order of magnitude compared to one without focusing.





Issues in the Analyzer (2)

Problem: Noise and EM interferences.

Solution: Proper shielding and LPF to isolate the device from noise source.

Result: Background noise is reduced from ~ 100 mV to ~ 2 mV, improve the resolution further... 



Issues in the Analyzer (3)

Problem: Data taking and analysis efficiency and limited step size to change the retarding voltage

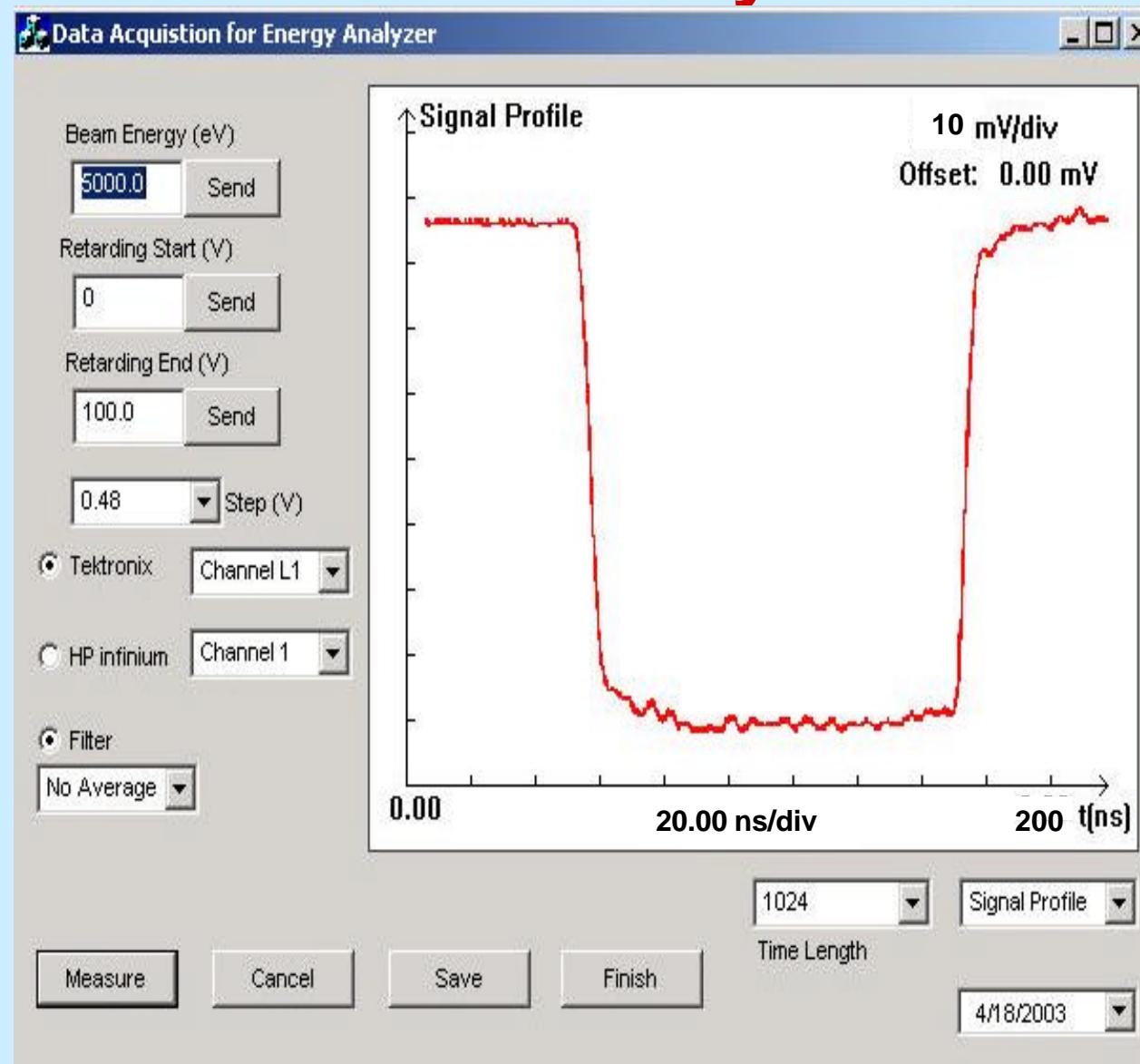
Solution: Computer automated system.

Result: Data taking time was reduced by more than 10 times. Instant measurement results. Minimal step size= 0.1 V, energy spread resolution improved further...





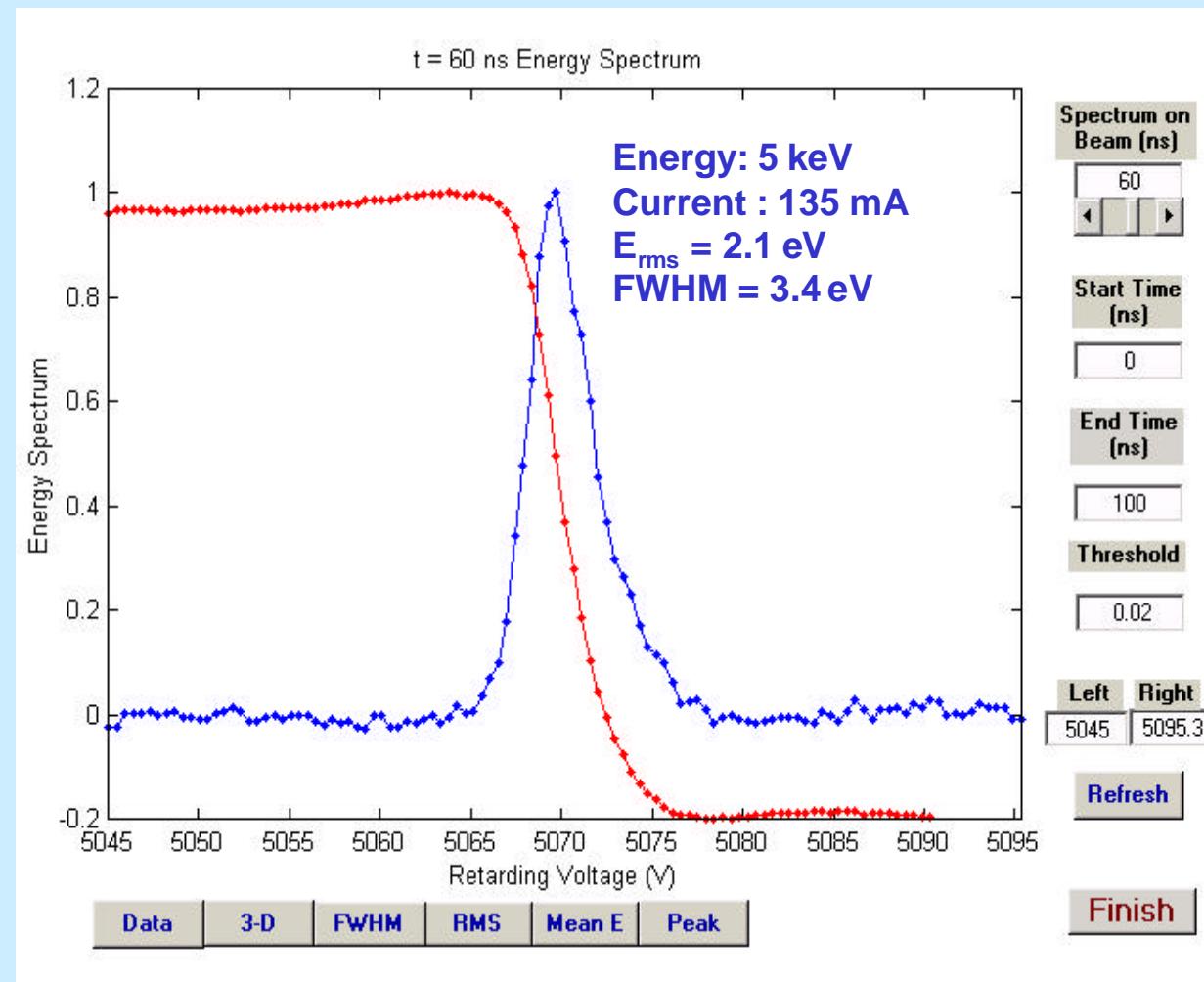
Data Taking interface for Energy Analyzer



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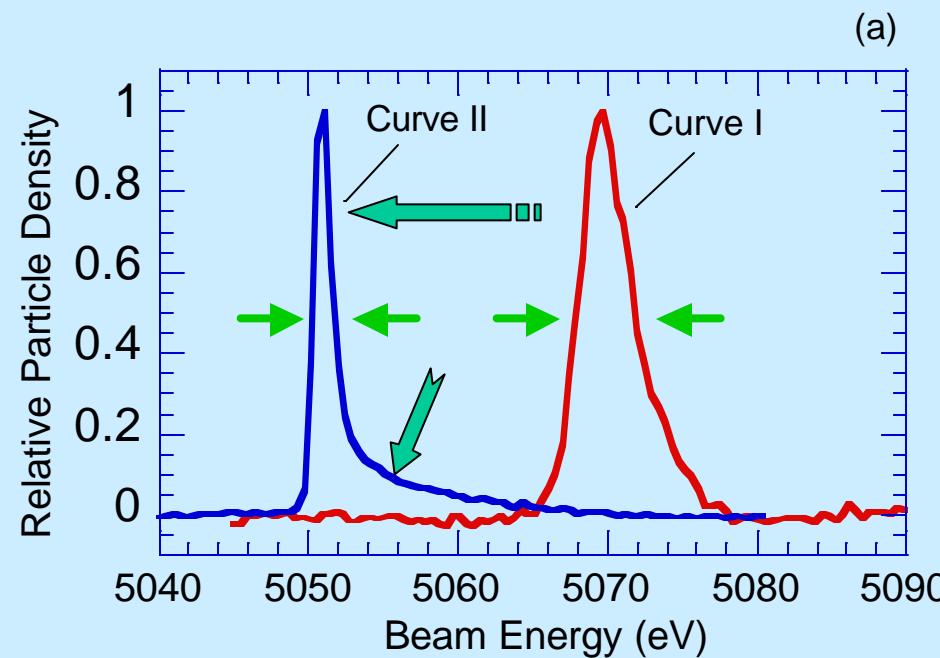
Data Analysis interface for Energy Analyzer



Issues in the Analyzer (4)

Longitudinal space-charge effect inside the Analyzer

- Problems:**
- Shift the measured mean energy towards low-energy side.
 - Leave a large tail at the high-energy side.
 - Make the FWHM of measured spectrum narrower than the true spectrum
 - Measured rms energy spread are different

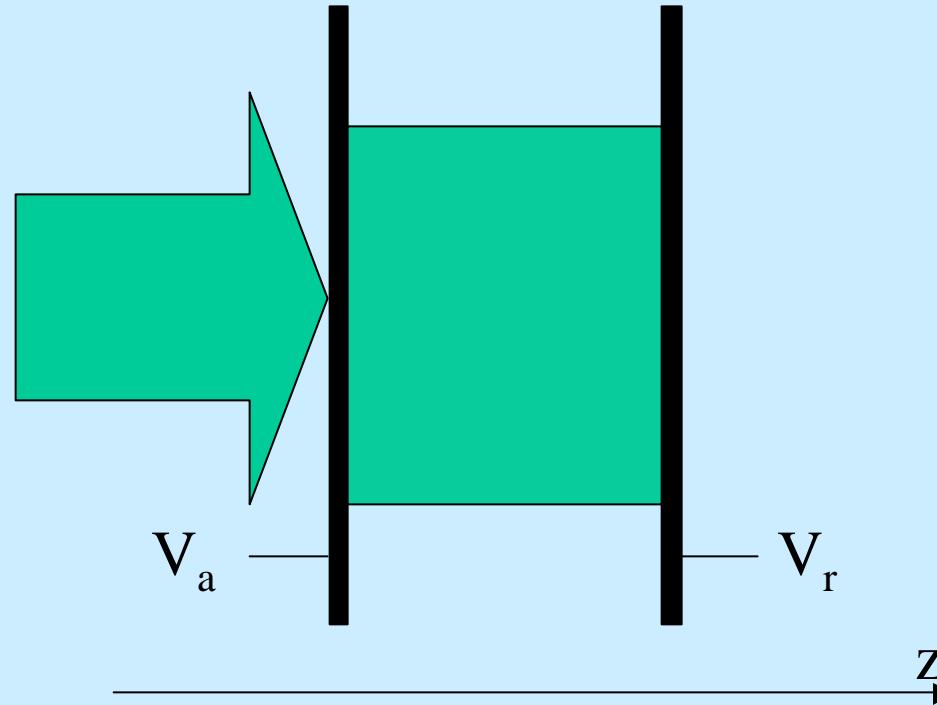


Parameters: 5 keV, 135 mA beam,

Curve 1: 0.2 mA beam current inside the device

Curve 2: 2.2 mA beam current inside the device

1D Modeling of Retarding Field Energy^[1]



Two models:

- Monoenergetic beam with energy eV_a
- Thermal Beam with initial temperature

[1] Submitted to PAC2003 and Phys. Rev. ST Acc. Beam



Poisson Equation in the System

Model I, monoenergetic beam:

$$\frac{d^2V}{dz^2} = -\frac{r}{e_0} = -\frac{J}{e_0 \sqrt{\frac{2qV}{m}}} = CJV^{-1/2}$$

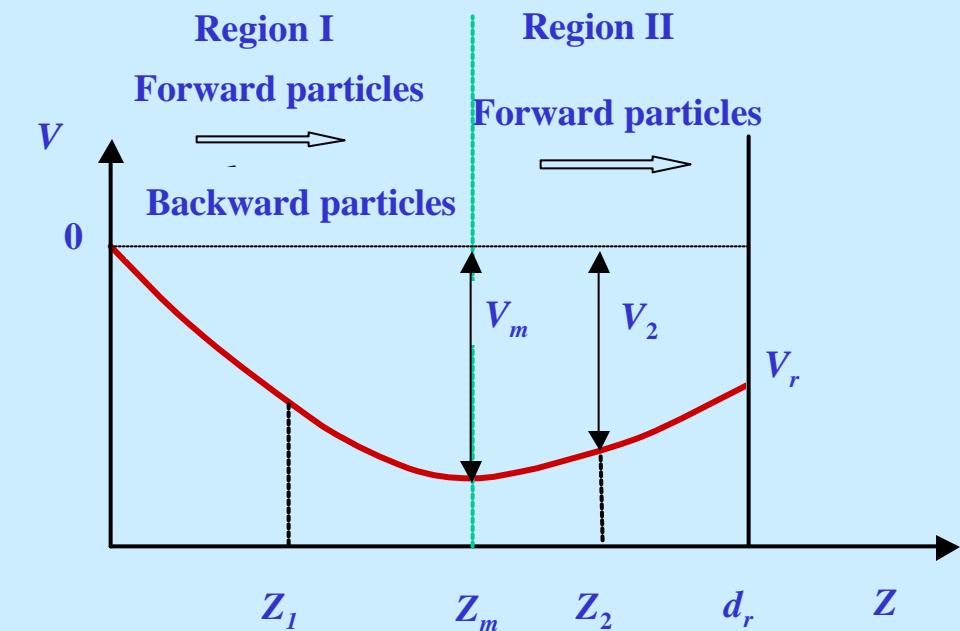
Model II, thermal beam:

$$V''(z) = -\frac{q}{e_0} \left(\int_0^\infty f_z(v_z) dv_z + \int_0^{\sqrt{2h(V(z)-V_m)}} f_z(v_z) dv_z \right)$$

$$V_2''(z) = -\frac{q}{e_0} \int_{\sqrt{2h(V(z)-V_m)}}^\infty f_z(v_z) dv_z$$

where

$$f_z(v_z) = f_0 \exp \left(-a^2 \left(\sqrt{v_z^2 - 2hV(z)} - v_0 \right)^2 \right)$$

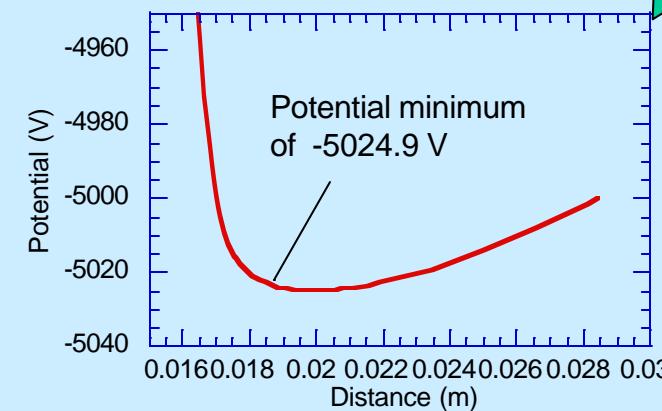
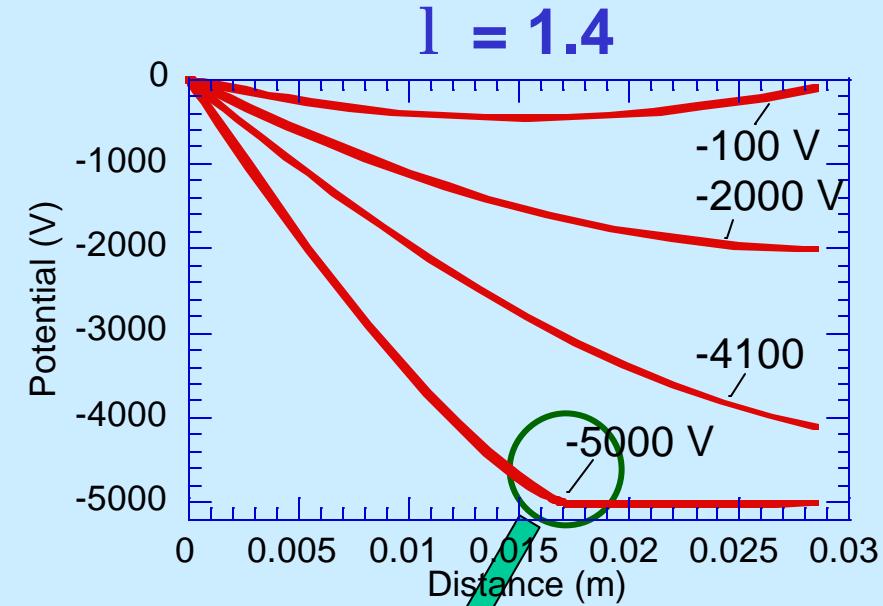
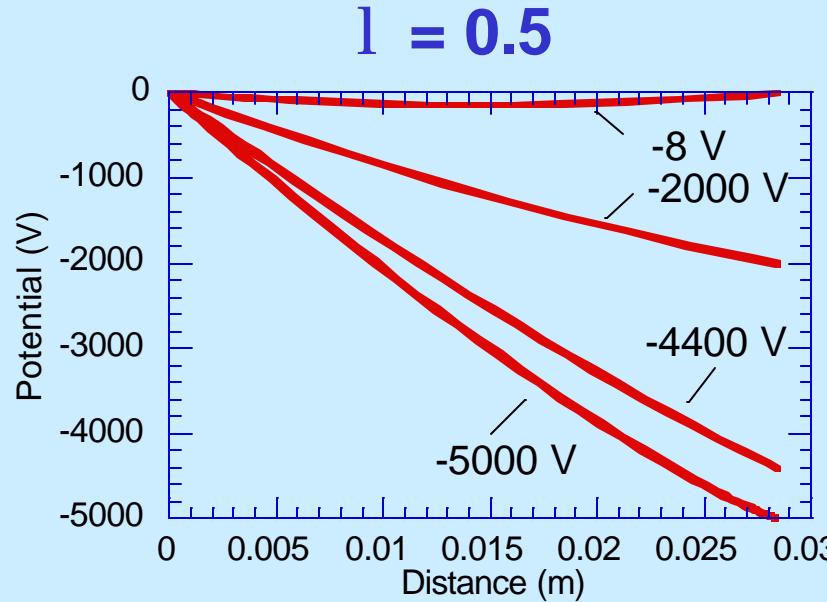




Potential solutions for thermal beam

Beam energy: 5 keV,

Initial beam energy spread: 10 eV ($\text{l} = \text{J}_{\text{in}}/\text{J}_{\text{lim}}$)

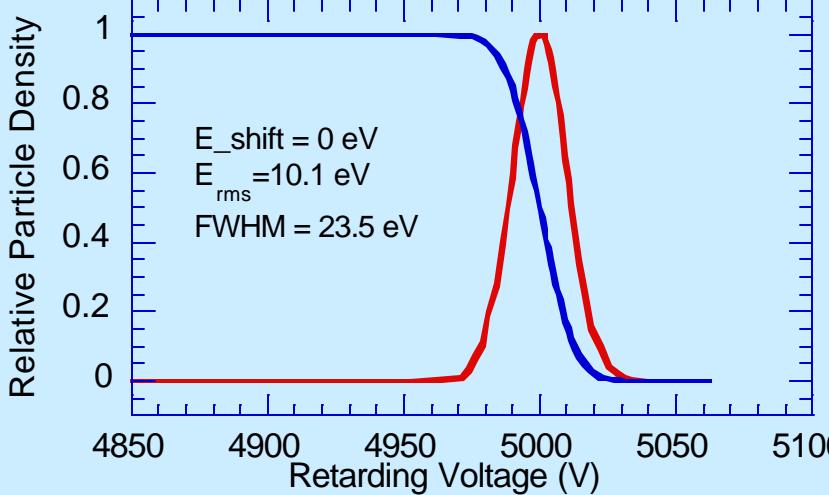




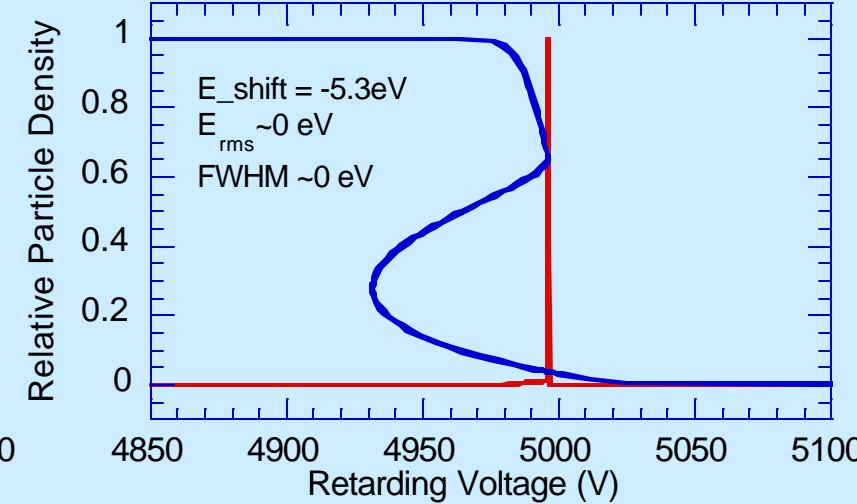
Calculated Energy Spectrum

Input: Beam energy = 5 keV, Energy Spread = 10 eV

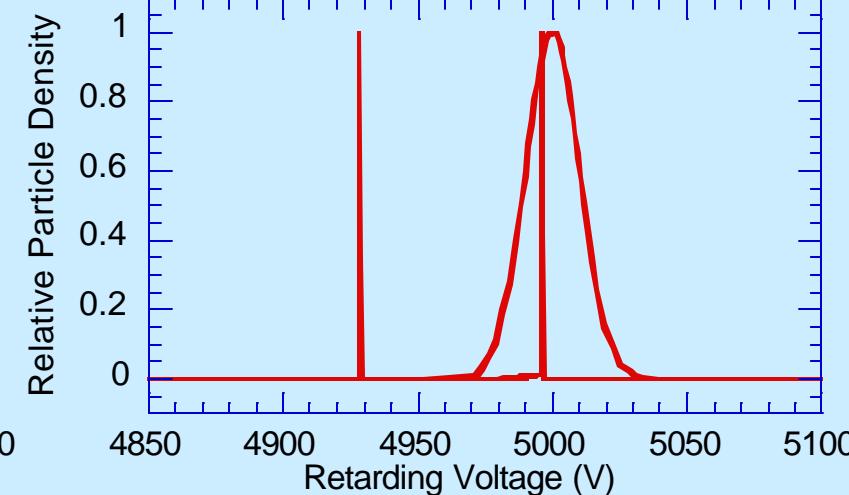
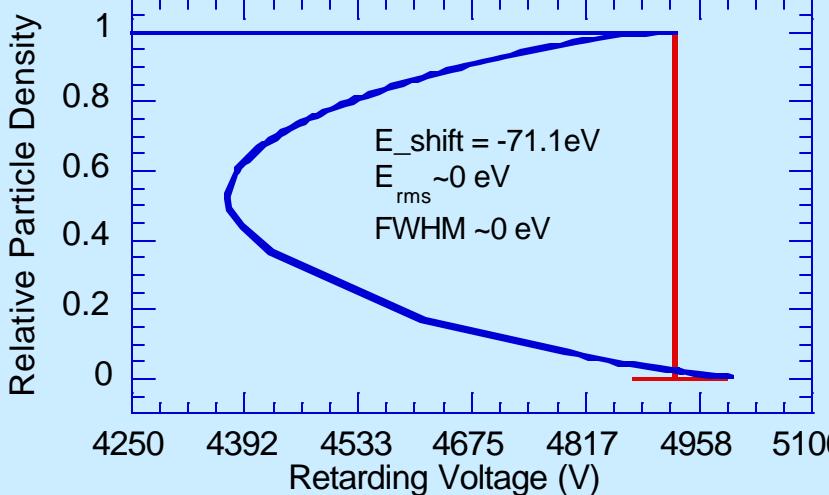
$l = 0.5$



$l = 0.8$



$l = 1.4$



Comparison of Simulation Results and Experiments

Experiment:

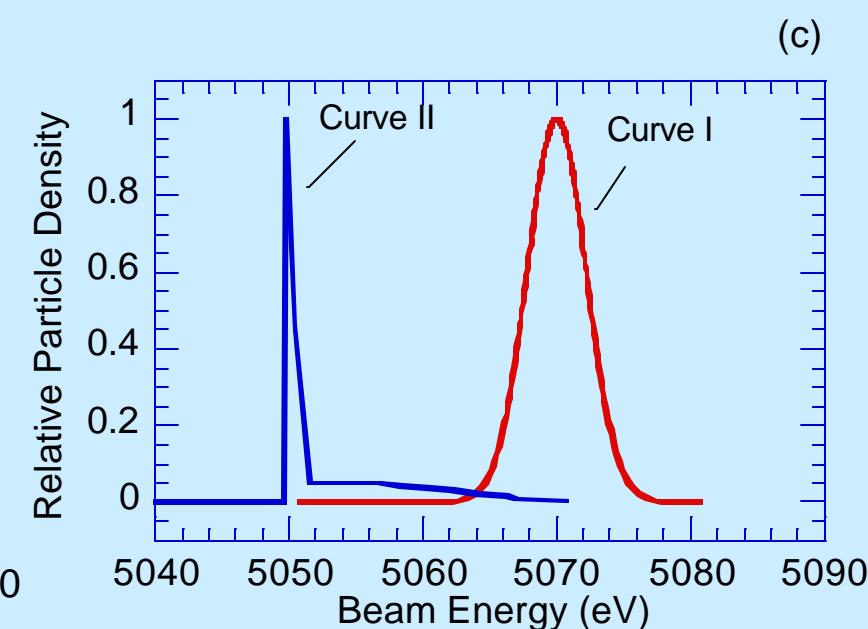
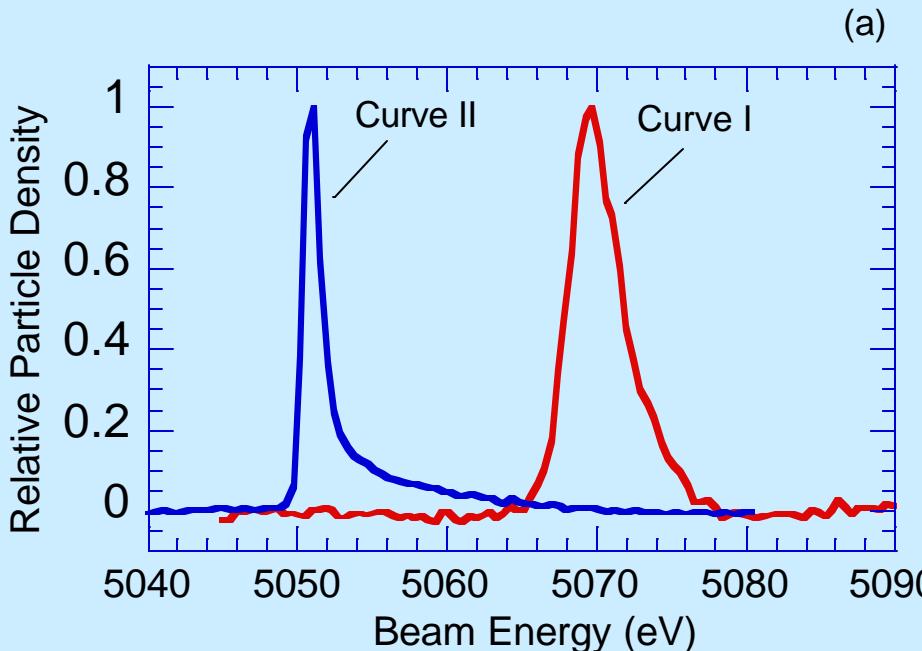
- Curve I: 0.2 mA inside the device ($I = 0.062$, estimated), $E_{rms} = 2.2$ eV, FWHM=3.4 eV
- Curve II: 2.2 mA inside the device ($I = 0.8$, estimated), $E_{rms} = 3.2$ eV, FWHM=1.1 eV

Nominal Energy : 5 keV, Current: 135 mA

1D Theory and simulation plus 2D correction:

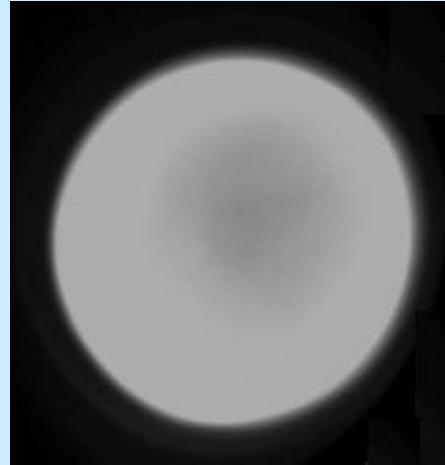
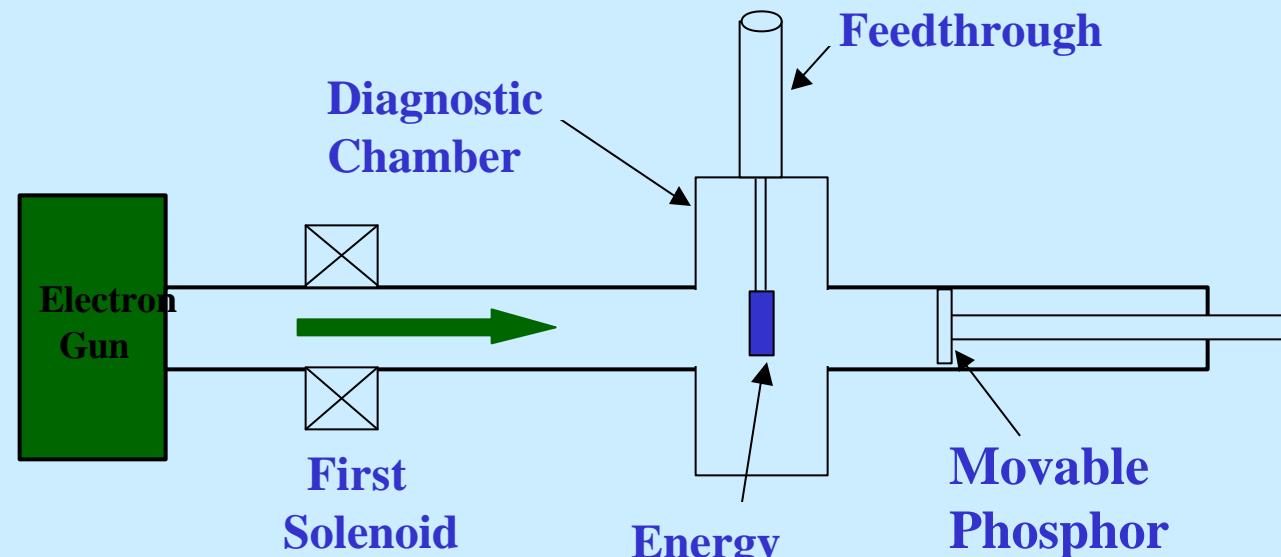
- Curve I: $I = 0.062$, $E_{rms} = 2.2$ eV, FWHM = 5.1eV

Curve II: $I = 1.2$, $E_{rms} = 5.1$ eV, FWHM = 0.49 eV

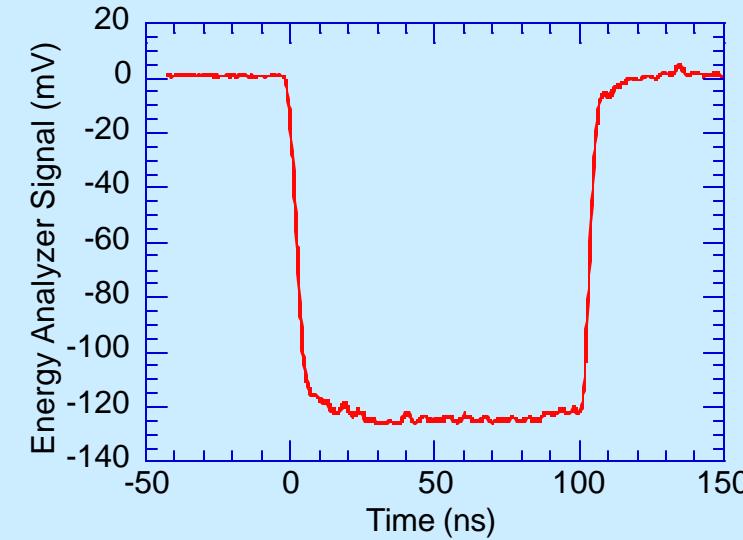




Phase I Experimental Setup



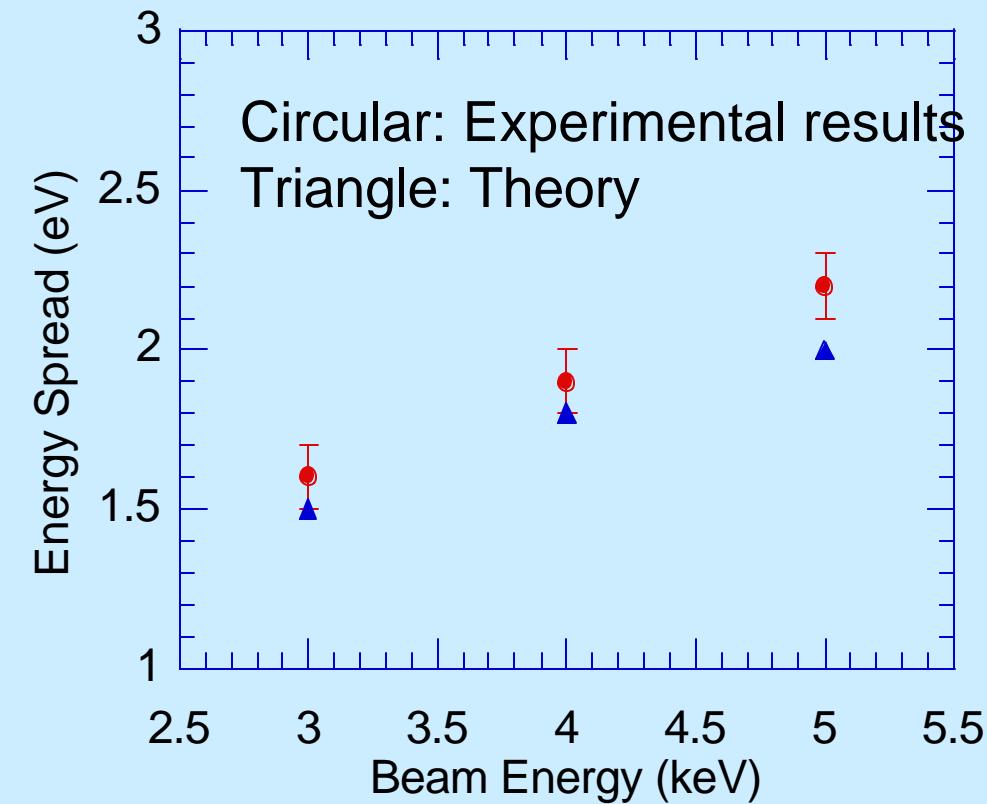
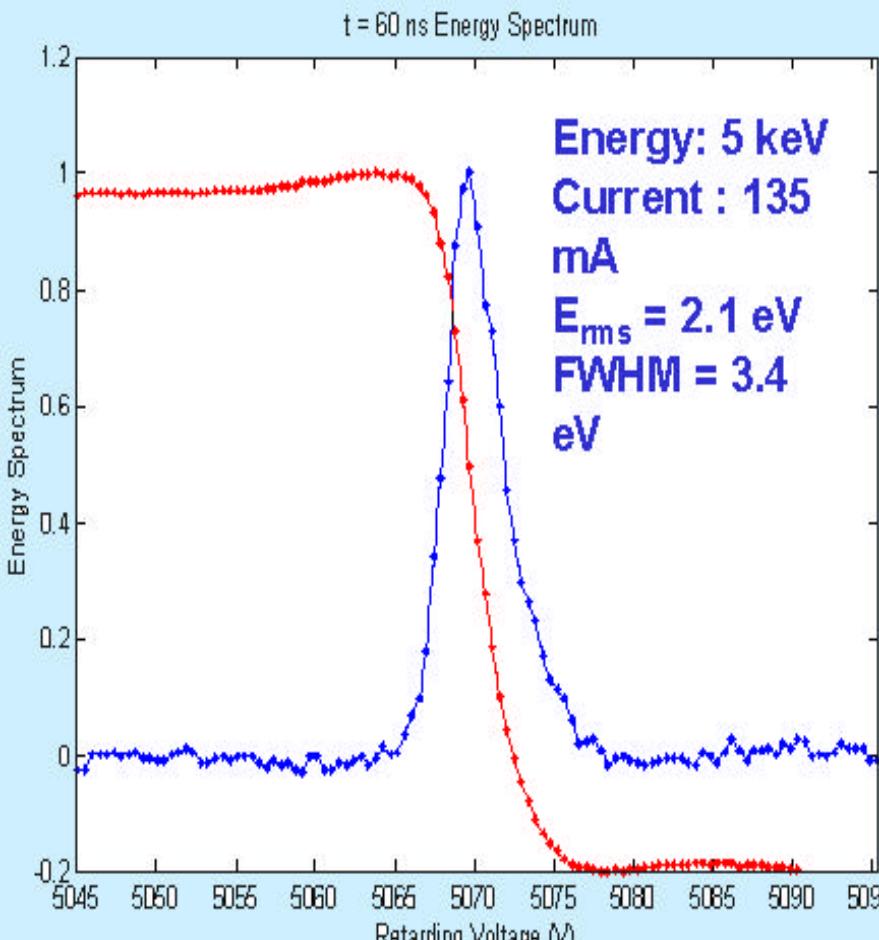
Phosphor screen image



Typical EA Signal

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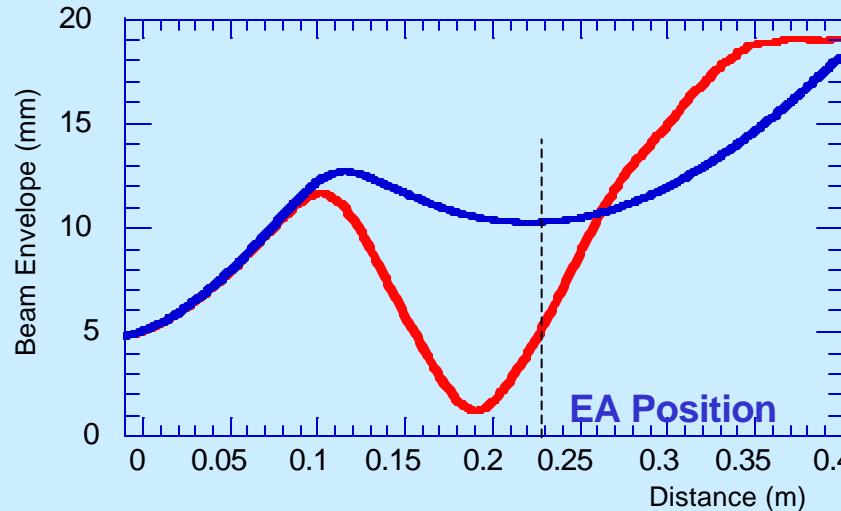
Typical Energy Spread Measurement Results



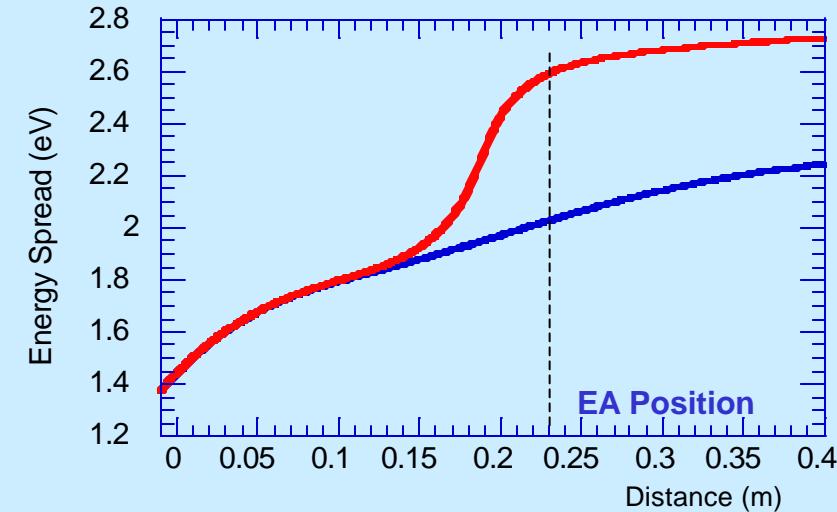


Energy Spread vs Beam Energy at Different Particle Densities

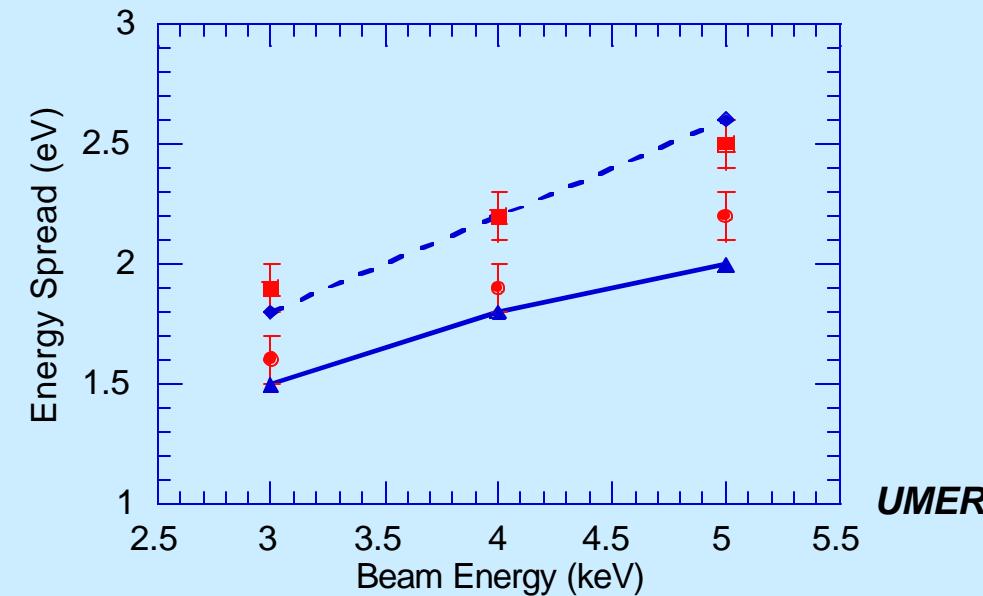
Beam envelope (5 keV)



Calculated energy spread



Comparison of experimental results and theory

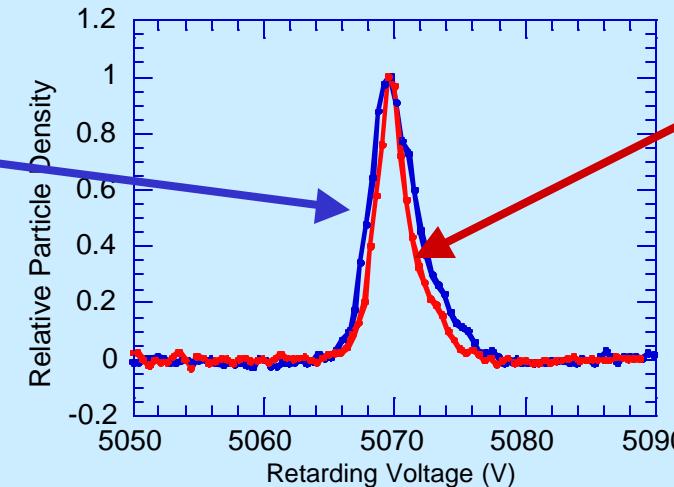




Energy Spread at Different Beam Currents

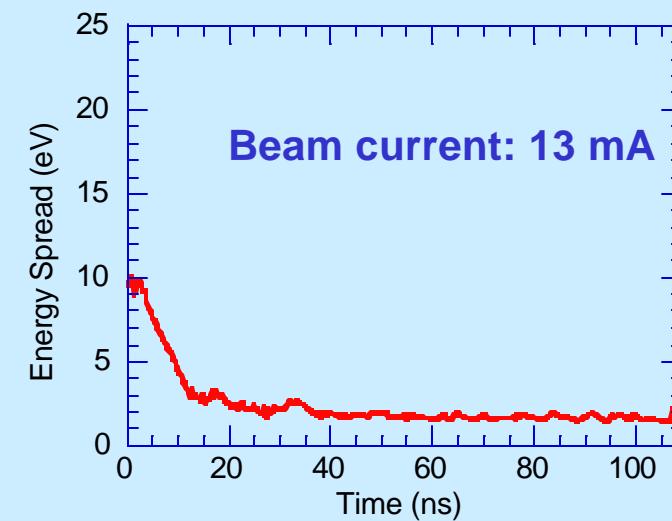
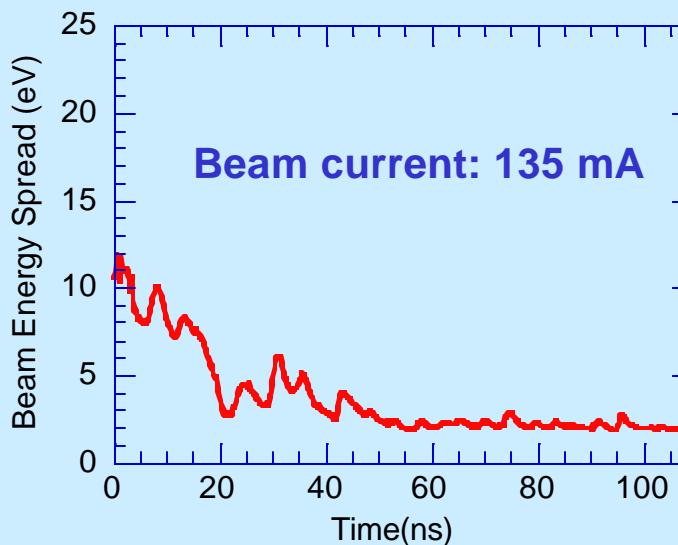
Beam Energy : 5 keV, Sampled position: 60 nS

Beam current: 135 mA
Energy spread: 2.1 eV



Beam current: 13 mA
Energy spread: 1.7 eV

Energy spread along the pulse (time resolved)

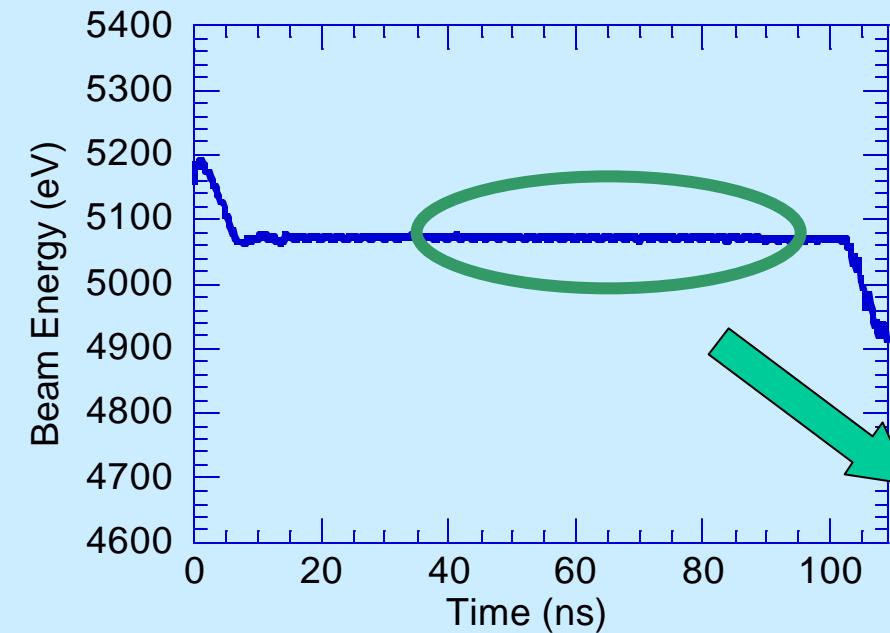




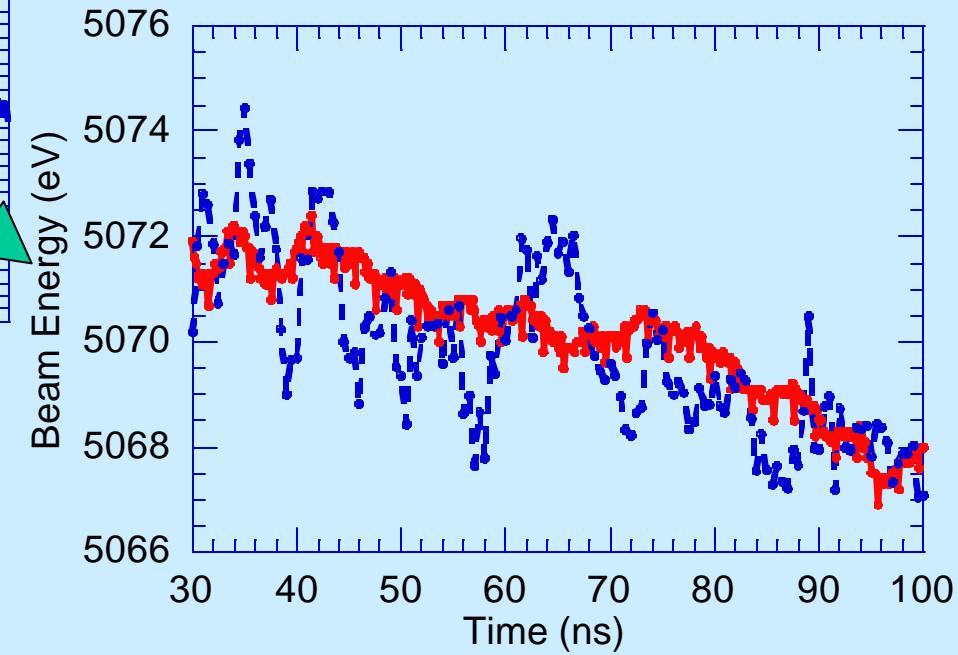
Experimental Results

Beam Energy : 5 keV,
Location: 25 cm from anode

Mean energy along the pulse

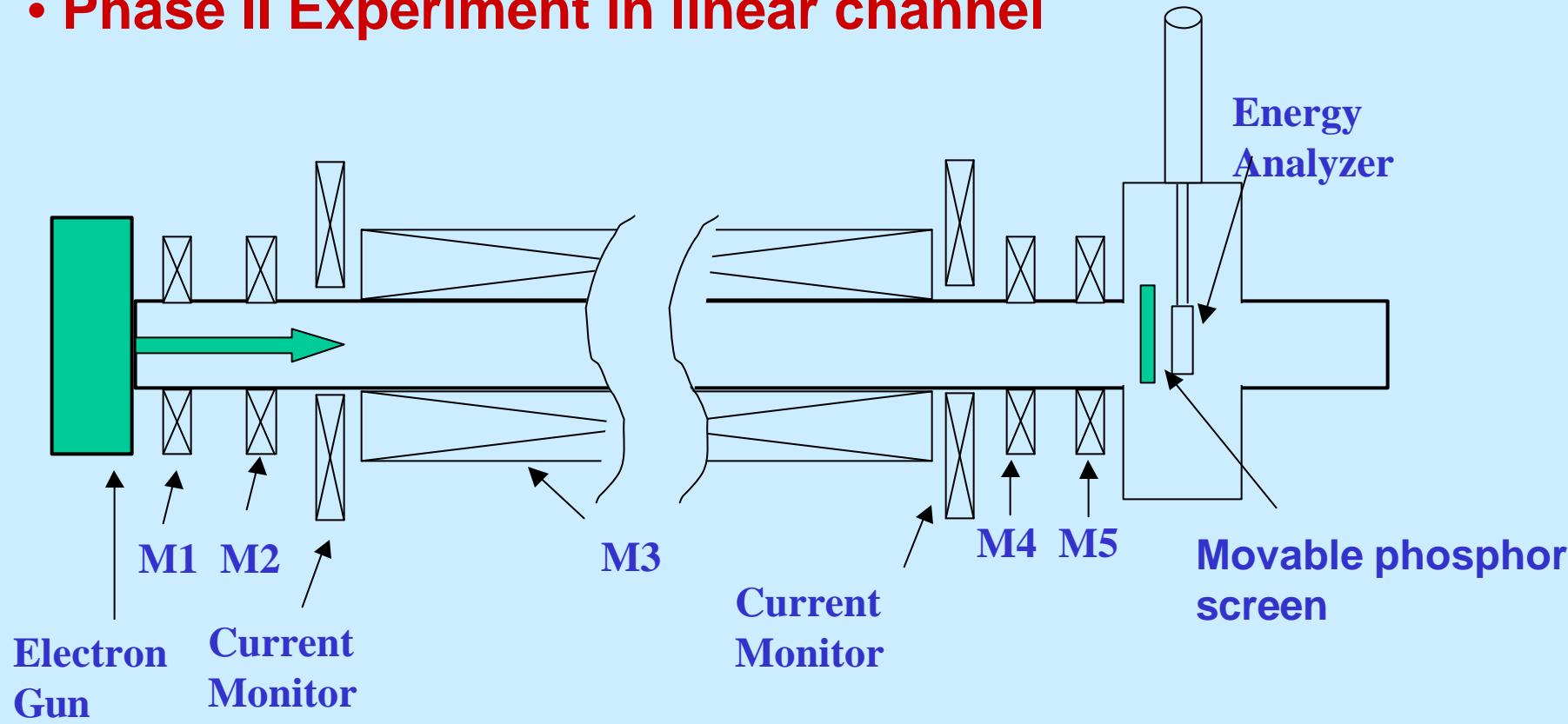


Zoom out



Future work

- Phase II Experiment in linear channel



- Characterize the energy spread increase in UMER
- Realistic simulation to correlate the energy spread and IBS ?

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Summary

- An experiment to study the energy spread evolution due to the intra beam scattering and other mechanisms in the space-charge dominated beam has been designed and is being carried out.
- A compact, high-precision retarding field energy analyzer system has been designed and tested. Understandings of several issues inside the device have significantly improved the device resolution.
- The results of phase I experiment show excellent agreement between the experiments and the theory (Boersch effect and Longitudinal-Longitudinal effect).
- The phase II experiment is under way to measure the energy spread increase in longer distance.